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USDA Forest Service
Research Paper RM-96
October 1972

FLOW AND CHANNEL CHARACTERISTICS OF TWO HIGH MOUNTAIN STREAMS

Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado

by Burchard H. Heede

ABSTRACT

Steps provided by logs fallen across the channel added to flow energy reduction. The streams required an additional number of gravel bars to adjust to slope. Average step length between logs and gravel bars are strongly related to channel gradient and median bed material size. More bars formed when fewer numbers of logs were available. Although these are "rushing mountain streams," most values for flow velocities ranged between 0.5 and 2.5 feet per second. Exponents of functions expressing rate of change of depth or velocity, respectively, with discharge, indicated that dynamic stream equilibrium was attained. Implications for forest management are that sanitation cuttings (removal of dead and dying trees) would not be permissible where dynamic stream equilibrium exists and bed material movement should be minimized.

Keywords: Mountain streams, hydraulic geometry, step formations, bed material movement, flood plain forest management.

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[1] *Central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted while author was assigned to Fort Collins; he is now located at the Station's Albuquerque field unit, in cooperation with the University of New Mexico.*

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Burchard H. Heede

Many small streams constitute the arteries by which much of the water stored in the high mountain snowpacks of Colorado is conveyed to the lowlands for people and industry. With increasing demands for water, manipulation of the small mountain streams can be expected to increase. Very little is known about flow and channel characteristics of these small streams. The acquisition of such knowledge is important as a safeguard against misuse and to assure clean water.

Study Area

The study streams, Fool Creek and Deadhorse Creek, lie within the Fraser Experimental Forest, approximately 50 miles west of Denver, Colorado. Both streams originate above timberline at an elevation of about 11,500 feet. Channel reaches studied were above 9,600 feet on Fool Creek and 9,300 feet on Deadhorse Creek.

The climate is cool, with an average yearly temperature of about 35° F. Annual precipitation averages 24 inches and varies from 15 to 30 inches; two-thirds of the precipitation occurs as snowfall. Streamflows generally reach a minimum in early April and peak in mid-June. During the record period 1952-65, the annual peak flow of Fool Creek averaged 14.2 cubic feet per second (c.f.s.), while the largest peak was 24.3 c.f.s. Deadhorse Creek had an average peak of 7.8 c.f.s. and a maximum of 13.6 c.f.s.

Flow levels decrease rapidly after the spring peak has passed. The winter low flows of both streams generally do not carry more than 0.3 c.f.s. Approximately 80 percent of the total yearly flow occurs between April and October.

Sediment loads are extremely small in both streams. Average annual sediment yield for the 5-year period preceding this study was 297 ft^3/mi^2 from Fool Creek and 147 ft^3/mi^2 from Deadhorse Creek (Leaf 1966). This yield estimate was based on the sediment load collected in sediment basins below the study reaches.

Fool Creek is characterized by long, gentle, relatively uniform slopes, whereas on Deadhorse Creek, slopes are less uniform and somewhat steeper. The median slopes of Fool Creek and Deadhorse are approximately 26 and 36 percent, respectively.

The parent material of soils on the watersheds was derived primarily from gneiss and schist (Retzer 1962). Typical soils contain angular gravel and stone, and a small amount of silt and clay.

Long stretches of both streams are embedded in alluvium. Some reaches are lined with rock outcrops and to a lesser extent by boggy soils. All reaches have rocky bottoms. Sand and gravel typically accumulate behind barriers across the channels.

The forest, estimated to be between 250 and 400 years old, is composed of Engelmann spruce (Picea engelmanni Parry), subalpine fir (Abies lasiocarpa (Hook.) Nutt.), and lodgepole pine (Pinus contorta Dougl.). Half of the merchantable timber on the Fool Creek watershed was removed by alternate-strip clearcutting between 1954 and 1956 (Goodell 1958, Love and Goodell 1960). The primary access road on Fool Creek was located to avoid the main stream channel and to minimize soil disturbance. Timber was made accessible by spur roads spaced at approximately 400-foot intervals along the contour; the spurs were provided with adequate surface drainage and culverts at stream crossings. In 1957 spurs were seeded to grass and culverts were removed on alternate roads to reduce traffic. The forest on Deadhorse Creek is uncut, except for approximately 30 acres on the south slope, which was commercially clearcut between 1942-46.

Methods

Three reaches each of Fool Creek and Deadhorse Creek, located in the upper, middle, and lower segments of the streams, were selected for study. Lengths of the reaches ranged between 150 and 1,750 feet. Detail surveys were made of the longitudinal profiles and selected channel cross sections. Measurements were recorded to the closest 0.10 foot.

The detailed configurations of the longitudinal stream profiles were studied to determine those factors causing local flow accelerations and decelerations; most pronounced of these were numerous rock bars, logs, and combinations thereof crossing the streambeds. These barriers forced the water to overflow and created hydraulic jumps below. In some cases, the accumulations were so heavy that logs were completely covered by rocks. If evidence of a log could not be detected, the barrier was classed as a gravel bar.

Coarse bed material was sampled by a method similar to that by Wolman (1954). A marker at the tip of the observer's boot determined the sampling points while pacing the streambed. This method permits random sampling of individual particles in the bed, a great advantage over bulk-sampling techniques where large rocks are found. Since the streams studied have bottom widths of only a few feet, Wolman's grid layout was somewhat modified. Fifty-foot reaches were randomly determined, the centerline staked, and one transect on each side of this line sampled. Particles with intermediate axes up to 2 mm were classed as sand. All materials with an intermediate axis larger than 2 mm were grouped into 4 mm classes. Because silt and clay size classes were rarely available in the channel bottoms, they were eliminated from the count.

Seven cross sections on Fool Creek and five on Deadhorse Creek were marked with stakes set away from the banks so that points could be remeasured.

Stream gages are located at the downstream end of the lowest channel reach studied in both streams. The gage on Fool Creek is a combination of a San Dimas flume and two broad-crested weirs. Deadhorse is gaged with a 120° V-notch weir. Continuous flow records were available at both stations. Water temperatures were recorded at the Fool Creek flume.

The velocity at ungaged sites was determined with a current meter. Point velocities were measured at 0.2 and 0.8 foot below the water surface where depth permitted; otherwise, one velocity reading at 0.6-foot depth was obtained. Vertical velocity distributions were determined where possible with a pygmy current meter at 0.1-foot intervals. Flow depths were read from a lightweight velocity headrod.

Results

The most interesting profile characteristic is the relatively close spacing of gravel bars and log steps, ranging between 4.8 and 9.7 feet (table 1). A typical longitudinal profile of a reach on Deadhorse Creek is shown in figure 1; drops, as shown near stations 3 + 70, 4 + 50, and 4 + 70, are typically the result of accumulations of gravel behind bars or logs.

Average step length between logs within the upper and lower reaches was about the same. It is believed that this uniformity was due to random mortality of trees along the flood plain, and that adjustment of the stream to the slope was achieved by formation of gravel bars. The probability of such a relationship is supported by the strong correlation between step length and median bed material size and step length and channel gradient (figs. 2, 3). Step length decreases with increasing median bed material size and increasing channel gradient. These relations are in agreement with the findings of Judd (1963) and Hariri (1964). In each study stream, an average of 2.9 gravel bars per 50 feet of channel were added to the log steps, resulting in an average step length of 6.5 and 9.1 feet on Deadhorse and Fool Creek, respectively. Since average log step spacing is about the same in both lower and upper reaches, increases in spacings in the downstream direction (table 1), representing stream adjustment to reduced gradient, were accomplished by adjustment of gravel bar intervals.

Deadhorse Creek, having a much steeper channel gradient than Fool Creek and therefore a shorter spacing between bars and logs,

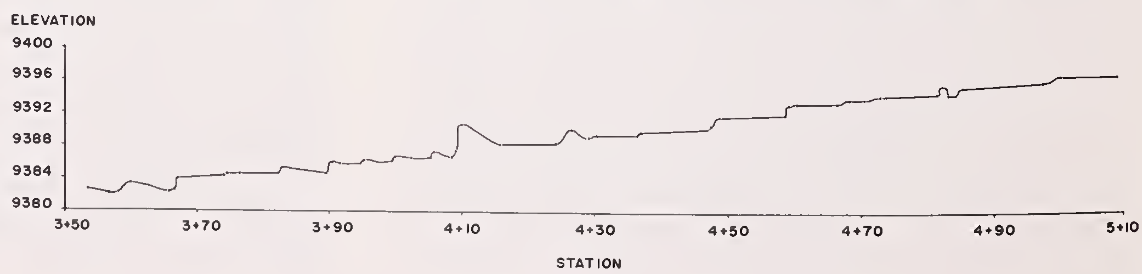

Figure 1. A typical longitudinal streambed profile representing a reach of Deadhorse Creek.

Table 1. Profile characteristics of Fool Creek and Deadhorse Creek

Item and unit of measure	Fool Creek		Deadhorse Creek	
	Lower	Upper	Lower	Upper
Total length of reach, ft.	1,756.1	552.8	927.0	404.8
Upper elevation, ft.	9,633.3	10,277.8	9,441.1	9,860.9
Lower elevation, ft.	9,495.0	10,180.0	9,350.0	9,770.0
Total fall, ft.	138.3	97.8	91.1	90.9
Average gradient	0.0787	0.1769	0.0983	0.2245
Number of logs	90	27	90	39
Number of bars	90	46	32	44
Average spacing between bars and logs, ft.	9.7	7.8	7.6	4.8
Maximum spacing between bars and logs, ft.	41.4	28.7	42.3	18.7
Minimum spacing between bars and logs, ft.	0.6	0.5	0.9	1.1
Average spacing of logs, ft.	19.5	20.4	10.3	10.4
Average gradient of channel bottom between bars and logs	-0.0214	0.0167	-0.0369	-0.0141
Number of bars and logs with available height information	152	54	116	79
Cumulative height of measured bars and logs, ft.	121.0	53.6	92.5	86.0
Average height of measured bars and logs, ft.	0.8	1.0	0.8	1.1

had about twice the number of logs. Logs per 50 feet of channel averaged 4.8 in Deadhorse and 2.5 in Fool Creek. An explanation for this difference is not readily apparent. Tree age, composition of species, and overall canopy density are quite similar along both streams. However, the growing site on the flood plain of Deadhorse is superior to that of Fool Creek because of richer soils.

The total fall of a reach of channel can be interpreted as an expression of potential energies. The total fall within the reaches studied is considerable, resulting in apparent channel gradients of 0.08 and 0.22 (table 1). These

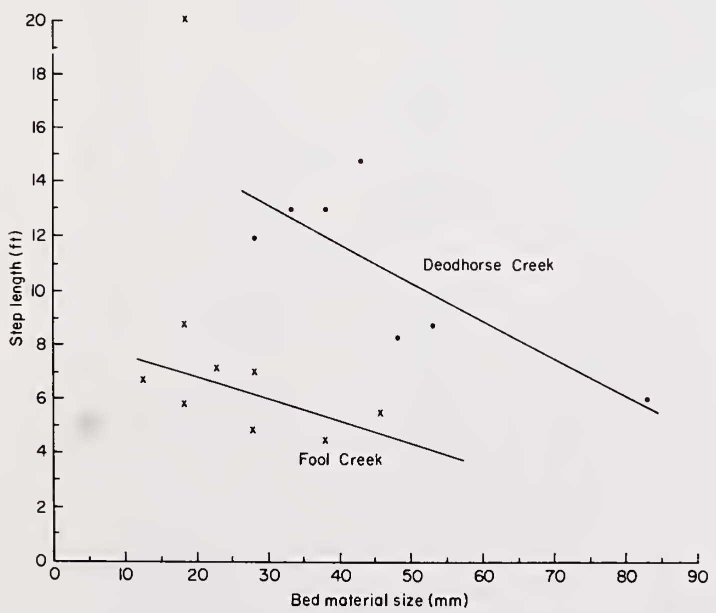

Figure 2. Relationship between step length of gravel bars and logs and median bed material size for Fool Creek and Deadhorse Creek.

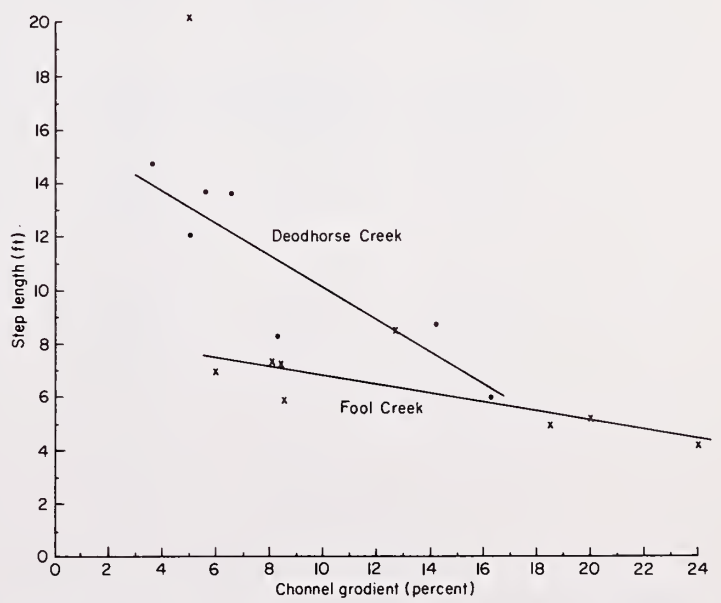

Figure 3. Relationship between step length of gravel bars and logs and channel gradient for Fool Creek and Deadhorse Creek.

gradients are misleading, however, since within each reach values for cumulative heights (above the bed) of gravel and log steps are between 50 and 100 percent of those of the total falls. This means that the potential energy is in part offset by the steps since below each step considerable energy is dissipated, and the flow must regain its momentum. Since, in many cases, a pronounced scour hole developed below the steps, a negative channel gradient was obtained for the slope between the steps.

Although Deadhorse Creek has a much steeper channel gradient than Fool Creek, it carries only half the sediment load. The mechanics of stream adjustment is a function of the interactions of many factors, but differences in the ratios between cumulative height of steps and total fall of bed may largely account for differences in the load characteristics of the streams.

	Ratio
FOOL CREEK	
Lower reach	0.87
Upper reach	.54
Average	.70
DEADHORSE CREEK	
Lower reach	1.01
Upper reach	.95
Average	.98

Cumulative height of steps nearly equals the total fall of the bed on Deadhorse Creek, while on Fool Creek cumulative step height is less than 75 percent of the total fall. Thus, the steepness of the channel gradient is more effectively offset by the formation of steps on Deadhorse than on Fool Creek, and less energy is available for transport of sediment on the former.

Table 2. Flow and channel characteristics of Deadhorse Creek

Cross section	Discharge (Q)	Mean velocity[1] (v)	Depth of flow: Max. (d_{max})	Depth of flow: Mean (d_m)	Bank to bank width (w)	Froude number[2] ($\mathbb{F}$)	Width-depth ratio $\left(\frac{w}{d_m}\right)$	Shape factor $\left(\frac{d_{max}}{d_m}\right)$
	c.f.s.	f.p.s.	Feet	Feet	Feet			
A	2.32	1.75	0.36	0.23	5.75	2.05	25.0	1.6
	2.20	1.58	.37	.24	5.75	1.81	24.0	1.5
	2.03	1.53	.35	.24	5.62	1.75	23.4	1.5
	1.78	1.39	.35	.22	5.80	1.66	26.4	1.6
	1.57	1.21	.33	.22	5.80	1.45	26.4	1.5
B	1.94	1.49	.97	.70	1.85	1.00	2.6	1.4
	1.72	1.35	.92	.69	1.85	.91	2.7	1.3
	1.59	1.17	.90	.68	2.00	.80	2.9	1.3
	1.32	1.03	.90	.64	1.85	.70	2.7	1.3
	1.73	1.30	.84	.66	2.00	.90	3.0	1.3
	1.55	1.25	.84	.67	1.85	.86	2.8	1.3
	1.09	1.11	.77	.53	1.85	.86	3.5	1.5
C	2.36	1.06	1.01	.93	2.40	.62	2.6	1.1
	1.68	.81	.93	.85	2.45	.49	2.9	1.1
	1.95	.98	.90	.81	2.45	.61	3.0	1.1
	.63	.37	.77	.69	2.45	.25	3.6	1.1
D	.77	1.45	.25	.14	3.85	2.18	27.5	1.8
	.24	.79	.21	.16	1.90	1.11	11.9	1.3
E	.74	1.06	.48	.20	3.55	1.33	17.8	2.0

[1] Based on point velocities measured by Pygmy current meter.

[2] $\mathbb{F} = \frac{v}{\sqrt{gd_m}}$, where g is the acceleration due to gravity.

The reduction of available energies by gravel and log steps, in combination with the roughness exerted by gravel beds and rock outcrops, is illustrated by the velocities of flow, which are indeed low for "rushing mountain streams." Mean velocities of Deadhorse Creek ranged from 0.37 to 1.75 feet per second (f.p.s.) (table 2) whereas velocities ranged from 0.52 to 4.85 f.p.s. on Fool Creek (table 3). Corresponding discharges were between 0.63 and 2.32 c.f.s. on Deadhorse and between 1.01 and 17.45 c.f.s. on Fool Creek. Most velocities of Deadhorse Creek fluctuated around 1 f.p.s. On Fool Creek, the value of 4.85 f.p.s. was measured only once; values usually ranged between 0.5 and 2.5 f.p.s.

Mean stream velocities are ordinarily determined from one- or two-point measurements in several vertical sections. This procedure, developed for large channels, assumes a logarithmic variation of velocity with depth. However, in turbulent, high-mountain streams the vertical velocity profiles do not resemble the logarithmic profile characteristics of larger channels. Standard depth levels for velocity measurements are therefore unrealistic for these streams.

Cumulative frequency curves of bed particle sizes for two reaches of Deadhorse Creek, typical for both streams, resemble the distribution often shown by river gravels (fig. 4). Ninety percent of the sample particles from the lower reach had a diameter of 50 mm or smaller, while 90 percent of the sample particles 800 feet upstream had diameters of 160 mm or smaller (fig. 4). This decrease in bed particle sizes in the downstream direction is characteristic of most streams, and is associated with a general decrease of the channel gradient downstream (fig. 5).

Because of the relatively steep banks and level channel bed (fig. 6), width varied very little with discharge at a station. Mean depths in Deadhorse Creek ranged between 0.14 and 0.93 foot for discharges between 0.77 and 2.36 c.f.s., and 0.20 to 1.05 feet for discharges between 0.97 and 7.14 c.f.s. in Fool Creek. Maximum depths ranged from 0.21 to 1.01 feet for discharges of 0.24 to 2.36 c.f.s. in Deadhorse Creek, and 0.27 to 1.60 feet at 0.97 to 10.30 c.f.s. in Fool Creek. These data indicate that the rapid increase of depth with discharge will lead to submergence of gravel and log steps at extreme flows. Such submergence did not occur during the study period.

If width and depth are considered together, such as in the width-depth ratio, a quantitative expression of channel shape will be obtained because relative rates of increase of width and depth are functions of channel shape. In cross sections with pure geometric shapes, the following relationships exist: in a triangular-shaped channel, the width-depth ratio remains constant with changing discharge; the width-depth ratio decreases in trapezoidal and elliptical cross sections when discharge increases; width-depth ratio decreases much more rapidly with in-

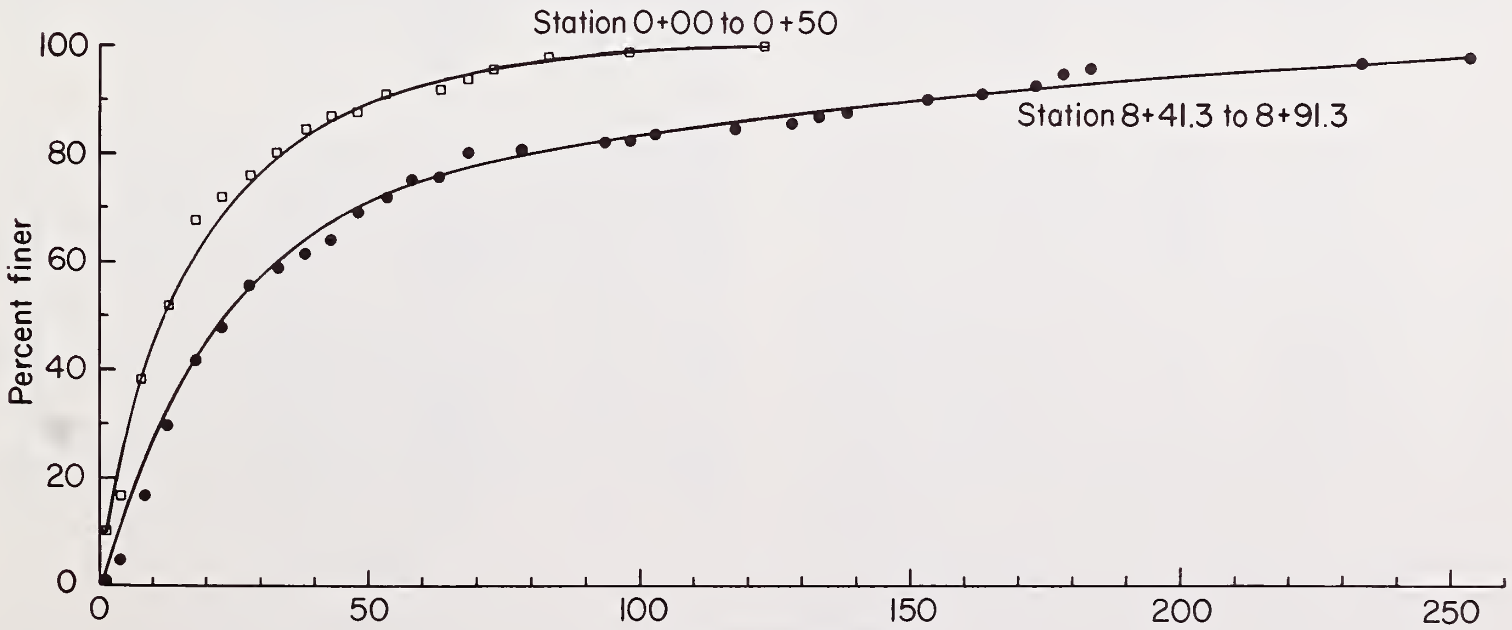

Figure 4. Bed particle size distribution for two reaches of Deadhorse Creek.

Table 3. Flow and channel characteristics of Fool Creek

Cross section	Discharge (Q)	Mean velocity[1] (v)	Depth of flow: Max. (d_{max})	Depth of flow: Mean (d_m)	Bank to bank width (w)	Water temperature	Reynolds number[2] ($\mathbb{R}$)	Froude number[3] ($\mathbb{F}$)	Width-depth ratio $\left(\frac{w}{d_m}\right)$	Shape factor $\left(\frac{d_{max}}{d_m}\right)$
	c.f.s.	f.p.s.	Feet			°F				
A	6.11	2.07	0.62	0.49	6.00			1.60	12.2	1.3
	4.75	1.78	.62	.45	6.00			1.49	13.3	1.4
	7.18	2.47	.71	.49	6.00			1.98	12.2	1.5
	5.14	1.91	.64	.45	6.00			1.60	13.3	1.4
	7.80	2.66	.64	.49	6.00			2.13	12.2	1.3
	8.44	2.33	.76	.61	6.00			1.67	9.8	1.3
	6.52	2.08	.75	.52	6.00			1.62	11.5	1.4
	8.65	2.33	.82	.62	6.00			1.66	9.7	1.3
	3.81	1.91	.73	.32	6.30	37	34,500	1.89	19.7	2.3
	4.15	2.09	.68	.32	6.30	42	41,300	2.07	19.7	2.1
	3.02	1.76	.65	.27	6.30	44	30,300	1.90	23.3	2.4
	1.65	1.15	.59	.23	6.30	45	17,200	1.35	27.4	2.6
	2.56	1.43	.66	.28	6.30	43	25,200	1.52	22.5	2.4
	1.94	1.51	.53	.22	5.90	47	22,300	1.81	26.8	2.4
B	17.45	4.85	1.16	.90	4.00			2.87	4.4	1.3
	11.04	3.76	1.07	.84	3.50			2.30	4.2	1.3
	5.80	2.24	1.05	.74	3.50			1.46	4.7	1.4
	8.38	2.51	1.29	.84	4.00			1.54	4.8	1.5
	7.76	2.27	1.33	.86	4.00			1.37	4.7	1.6
	2.51	1.27	.93	.53	3.75	37	38,000	.98	7.1	1.8
	2.17	1.37	.77	.43	3.70	45	38,300	1.17	8.6	1.8
	1.56	1.22	.66	.35	3.70	45	27,700	1.16	10.6	1.9
	2.04	1.24	.80	.45	3.70	43	35,100	1.04	8.2	1.8
	1.31	1.06	.73	.34	3.70	47	24,200	1.02	10.9	2.2
C	9.40	2.51	1.25	1.03	3.65			1.39	3.5	1.2
	3.06	1.43	.86	.61	3.50	40	52,200	1.03	5.7	1.4
	1.61	.96	.71	.51	3.30	45	31,800	.75	6.5	1.4
	1.13	.79	.64	.43	3.30	45	21,400	.68	7.7	1.5
	1.58	.97	.70	.49	3.30	43	29,900	.78	6.7	1.4
	1.01	.72	.68	.42	3.30	46	20,000	.62	7.9	1.6
D	9.69	1.89	1.20	1.00	5.15			1.06	5.2	1.2
	8.91	1.81	1.09	.95	5.15			1.04	5.4	1.2
	3.21	.89	.86	.70	5.15	38	35,600	.60	7.4	1.2
	2.72	.90	.75	.59	5.15			.60	8.7	1.3
	2.52	.82	.84	.60	5.15	37	27,800	.59	8.6	1.4
	1.93	.74	.72	.51	5.15	46	25,000	.58	10.1	1.4
	1.43	.63	.60	.44	5.15	46	18,400	.53	11.7	1.4
	1.71	.80	.63	.41	5.15	46	21,700	.70	12.6	1.5
E	10.30	2.09	1.60	.92	5.35			1.22	5.8	1.7
	8.35	1.76	1.54	.89	5.35			1.05	6.0	1.7
	2.76	.91	1.32	.57	5.30	37	32,000	.68	9.3	2.3
	2.75	.84	1.30	.61	5.30	42	31,600	.52	8.7	2.1
	2.27	.83	1.10	.75	3.65			.54	4.6	1.5
	1.48	.73	1.01	.56	3.65	37	23,100	.55	6.5	1.8
	1.10	.58	1.00	.52	3.65	46	20,000	.45	7.0	1.9
	1.18	.61	1.00	.53	3.65	45	21,000	.47	6.9	1.9
	1.01	.52	.96	.63	3.10			.34	4.9	1.5
F	6.52	2.82	0.70	0.55	4.20			2.13	7.6	1.3
	4.91	2.59	.56	.45	4.20			2.17	9.3	1.2
	3.05	2.22	.46	.33	4.20	38	41,900	2.17	12.7	1.4
	1.59	1.91	.33	.26	3.20			2.10	12.3	1.3
	1.24	1.88	.28	.21	3.20	46	26,100	2.30	15.2	1.3
	.97	1.64	.27	.20	3.00	45	21,300	2.06	15.0	1.4
	1.04	1.68	.28	.21	3.00	46	23,400	2.06	14.3	1.3
G	7.14	2.39	1.23	1.05	2.85			1.31	2.7	1.2
	5.49	2.04	1.29	.94	2.85			1.18	3.0	1.4
	1.66	.99	.85	.62	2.70	39	35,900	.71	4.4	1.4
	2.15	1.14	.85	.70	2.70	41	47,000	.76	3.9	1.2
	1.23	.87	.72	.50	2.85			.69	5.7	1.4
	.84	.70	.57	.38	3.15	46	39,000	.64	8.3	1.5
	.74	.61	.65	.44	2.75	45	17,400	.52	6.3	1.5
	.78	.60	.63	.46	2.85	46	18,300	.50	6.2	1.4

[1] Based on point velocities attained by Pygmy current meter.

[2] $\mathbb{R} = \frac{vd_m}{\nu}$, where ν is the kinematic viscosity in ft.^{2}/second.

[3] $\mathbb{F} = \frac{v}{\sqrt{gd_m}}$, where g is the acceleration due to gravity taken as 32.2 ft./sec.^{2}.

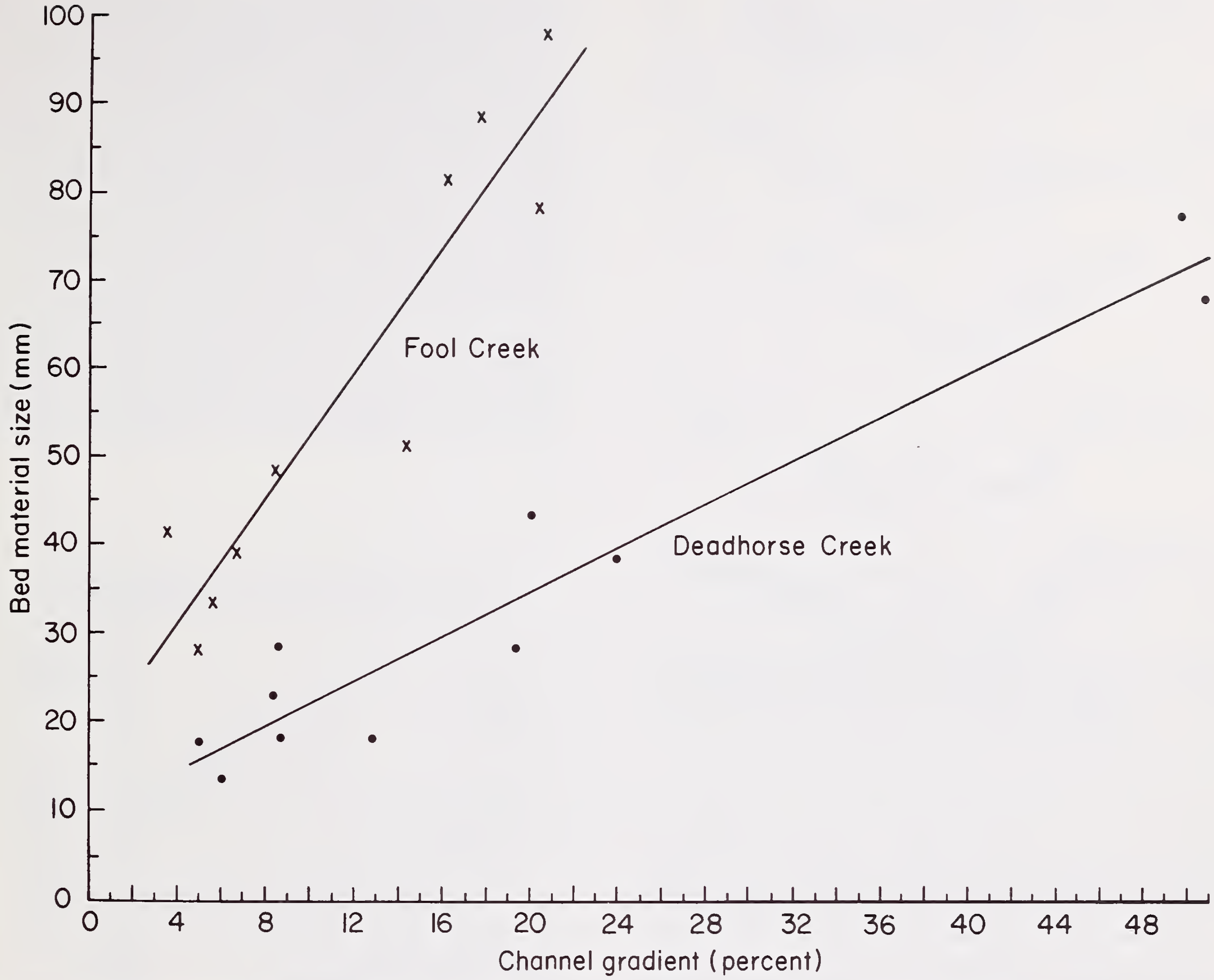

Figure 5. Relationship between median bed material size and channel gradient for Fool Creek and Deadhorse Creek.

creasing discharge in rectangular-shaped channels. The data in tables 2 and 3 show a rapid decrease in this ratio. For example, at Deadhorse Creek station B, the width-depth ratio decreased from 3.5 to 2.6, while the discharge increased from 1.09 to 1.94 c.f.s. At station A of Fool Creek, the width-depth ratio varied from 27.4 to 9.7 for discharges of 1.65 to 8.65 c.f.s.

When the width-depth ratio is expressed as a function of discharge at a station, a simple power function is derived:

$$w/d = rQ^{s}$$

where w/d is the width-depth ratio, Q is the discharge, and r and s are numerical coefficients. The value of s, the slope of the line resulting from a log-log plot of the equation, expresses the relative rate of decrease of the ratio with increasing discharge. An example from three stations is plotted in figure 7.

Channel shape can also be approximated by use of the shape factor, the quotient of maximum depth divided by mean depth. If such true geometric shapes as triangles, parabolas, and rectangles are considered, the respective shape factors would be 2.0, 1.5, and 1.0. The most effective hydraulic shape would be a semicircle, which normally does not exist in natural streams.

The last column of table 2 indicates that each cross section at Deadhorse Creek has a relatively uniform shape factor through the range of measured discharges. The table also shows that the shape factor is close to parabolic at station A, while nearly rectangular at

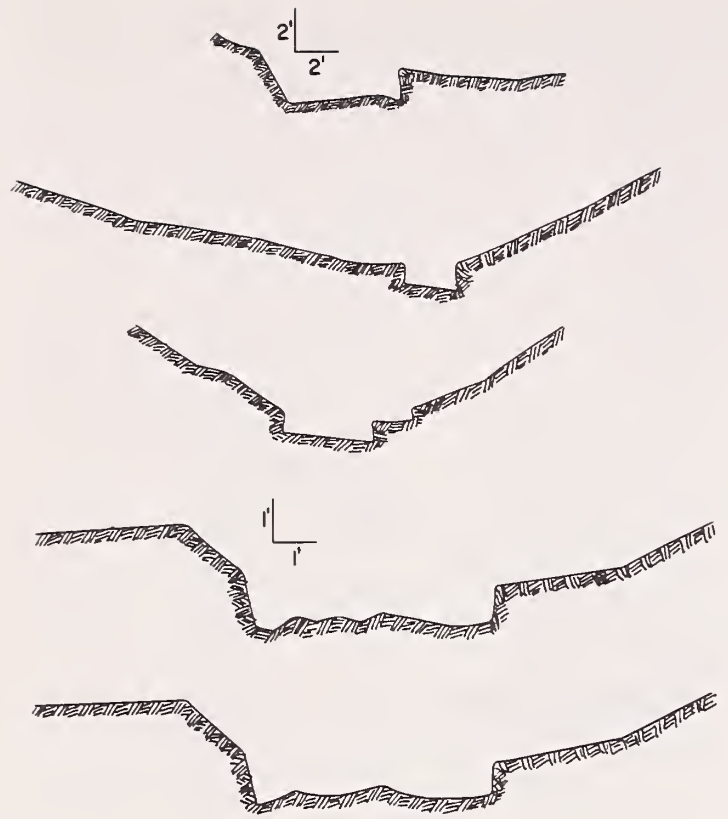

Figure 6. Typical channel cross sections for Deadhorse Creek (upper three) and Fool Creek (lower two).

station C. To verify shapes, the cross sections must be plotted because a variety of unusual sections can have the same shape factor.

Discharge measurements at Fool Creek had a larger range than those of Deadhorse Creek (table 3). This may be one of the reasons why the change in shape factors with changing discharge is much more pronounced at Fool Creek than at Deadhorse Creek. Increases in shape factor reflect a relative increase in the wetted perimeter, which increases roughness of flow and decreases channel efficiency. Thus, the hydraulic efficiency for the conveyance of water decreases at lower discharges. Such indications are given at Fool Creek station A where, at a discharge of 8.65 c.f.s., the shape factor was 1.3, while at a flow of 1.94 c.f.s., the shape factor increased to 2.4.

To test if the study streams behaved like larger streams, the methods developed by Leopold and Maddock (1953) for the treatment of hydraulic variables was applied. They found that hydraulic characteristics of stream channels such as depth, width, and velocity vary as some power function of the discharge as follows:

$$w = aQ^b,\ d = cQ^f,\ v = kQ^m$$

where w is the width, d is the mean depth, v is the velocity, and a, c, k, b, f, and m are numerical coefficients. Discharge is the product of cross-sectional area and mean velocity, or expressed algebraically, $Q = w \times d \times v$. Thus, $aQ^b \times cQ^f \times kQ^m = Q$, or $b + f + m = 1$, and $a \times c \times k = 1$. Since width changes very little with discharge, the slopes of the width-discharge curves would be near zero, and the respective exponent (b) would have a value close to zero. This is indicated by the sums of f and m, which are about 1.0 (table 4). The average values at a given station for f and m are 0.43 and 0.52, respectively. If the sums of f and m are compared with those derived from other streams and regions by other investigators (table 5), it appears that the Fool Creek data

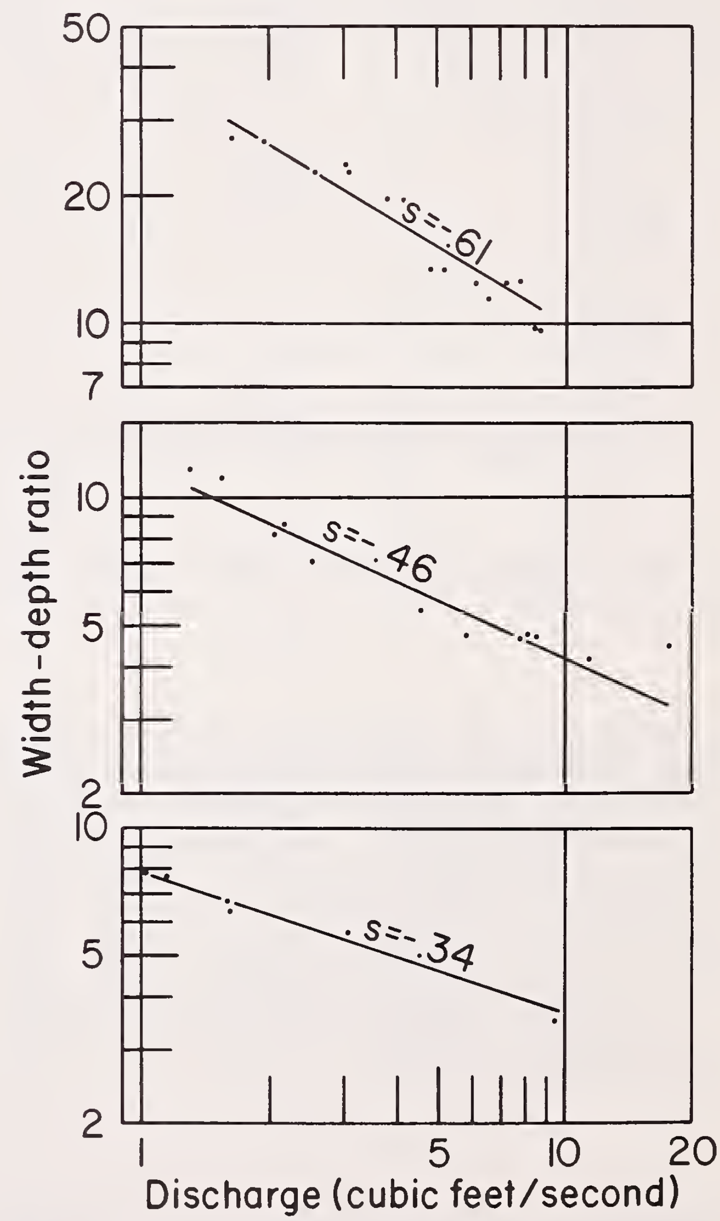

Figure 7. Typical relationships between width-depth ratio and discharge on Fool Creek.

are closest to those derived from a much larger mountain stream, Brandywine Creek in Pennsylvania (Wolman 1955). The relationships in figure 8, which show depth and velocity as a function of discharge, are believed to be representative of all cross sections in Fool Creek. Discharges of Deadhorse Creek were too small in magnitude relative to instrument errors to permit meaningful analytical treatment of the data.

As must be expected for a small, tumbling, high mountain stream whose bed is made up of coarse material, gravel bars, and log steps, Reynolds numbers ($\mathbb{R}$) were high — between 17,000 and 52,000 (table 3) — indicating highly turbulent flows. Froude numbers ($\mathbb{F}$) in both streams showed a spread of values between a

Table 4. Relation of depth (d) and velocity (v) to discharge[1] (Q), at different cross sections of Fool Creek

Cross sections	$d = cQ^f$	$v = kQ^m$	f + m
A	$0.14\ Q^{0.66}$	$1.09\ Q^{0.38}$	1.04
B	$.37\ Q^{0.36}$	$.67\ Q^{0.68}$	1.04
C	$.41\ Q^{0.41}$	$.75\ Q^{0.54}$	.95
D	$.39\ Q^{0.41}$	$.50\ Q^{0.59}$	1.00
E	$.53\ Q^{0.23}$	$.51\ Q^{0.59}$	.82
F	$.19\ Q^{0.54}$	$1.68\ Q^{0.27}$	.81
G	$.48\ Q^{0.40}$	$.74\ Q^{0.59}$	.99

[1] Symbols explained in text.

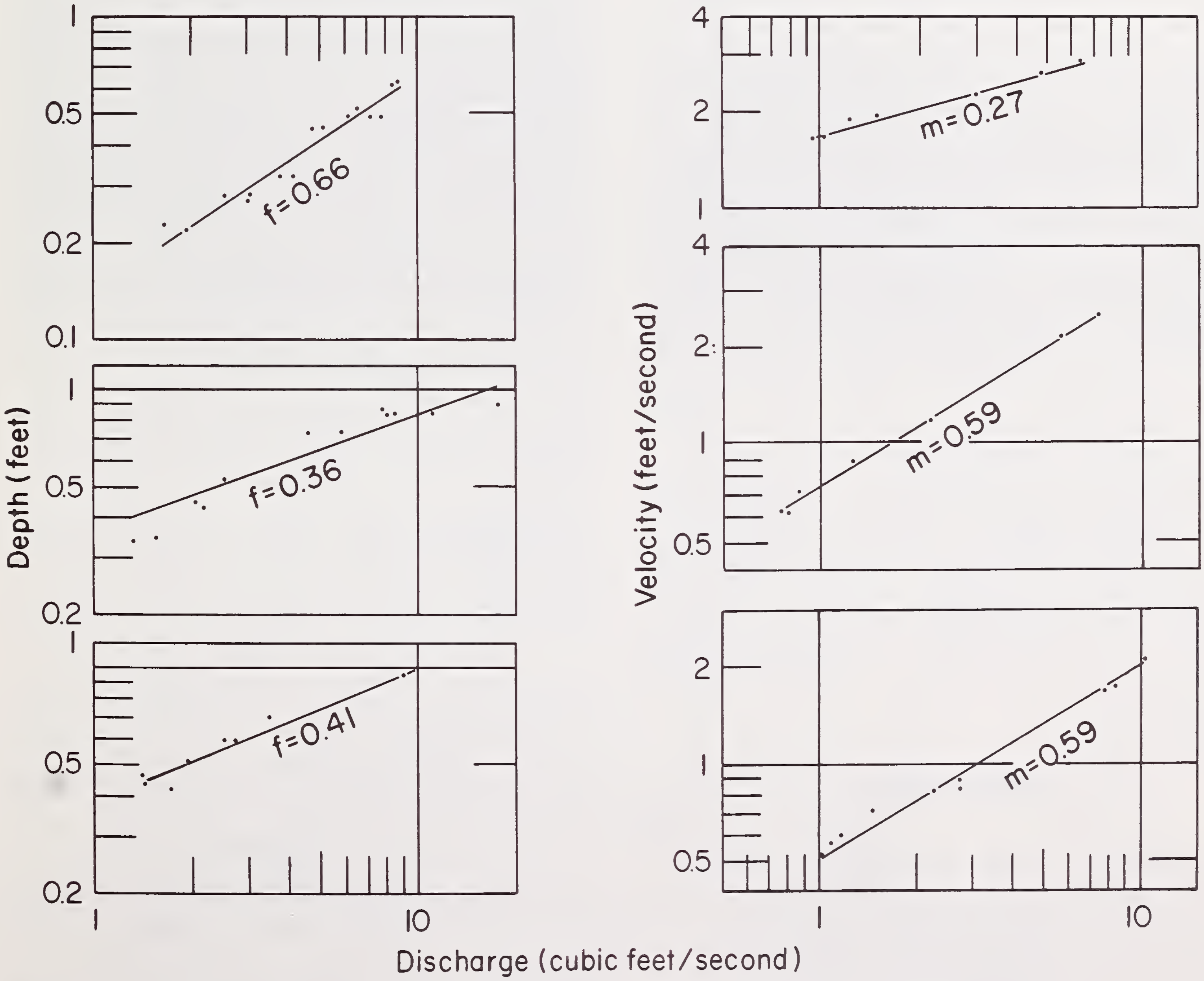

Figure 8. Depth and velocity as a function of discharge for typical cross sections on Fool Creek.

Table 5. Values of exponents[1] in the equations for the hydraulic geometry of stream channels; $d = cQ^f$ and $v = kQ^m$ (Average relations for a typical cross section)

Streams and location	f	m	f + m
Fool Creek, central Rocky Mountains	0.43	0.52	0.95
Brandywine Creek, Pennsylvania[2]	.41	.55	.96
Average values, midwestern United States[2]	.40	.34	.74
Ephemeral streams in semiarid United States	.36	.34	.70
Average of 158 gaging stations in United States[2]	.45	.43	.88
10 gaging stations on Rhine River, Europe[2]	.41	.43	.84

[1] Symbols explained in text.
[2] From Leopold, Wolman, and Miller (1964), p. 244.

few tenths and 2.9. The combined effect of viscosity and gravity (that is, considering the Reynolds number and the Froude number for a given flow) produced the following regimes of flow in Fool Creek: supercritical-turbulent, critical-turbulent, and subcritical-turbulent. Due to its unstable stage, the critical-turbulent regime may better be designated as transitional range because, at a Froude number of unity (critical), the flow will either go into a subcritical or supercritical state, or may fluctuate between both.

Water temperatures showed quite pronounced diurnal fluctuations during the summer months (fig. 9) and were directly related to air temperatures. In spite of heavy shading of the streams by relatively dense stands of trees, lag times between peak temperatures of air and water were practically nil. Temperatures increased from 36°F at 6:00 a.m. to 43°F at 1:00 p.m. on July 12.

Discussion

Detailed investigations of the longitudinal profiles showed that a great number of gravel bars and logs crossed the channel. The logs accumulated gravel and thus formed steps. Since step spacing between the logs did not change within individual channel reaches, the remaining adjustment of the streams to slope was achieved by gravel bar formation. Step length decreased with increasing channel gradient and increasing median bed material size. The cumulative height of steps formed by logs and gravel bars nearly offset the total fall of Deadhorse Creek, and approached 75 percent of the fall of Fool Creek. Bars and logs together provided an average of 7.7 and 5.4 energy dissipators for 50 feet of channel on Deadhorse and on Fool Creek, respectively.

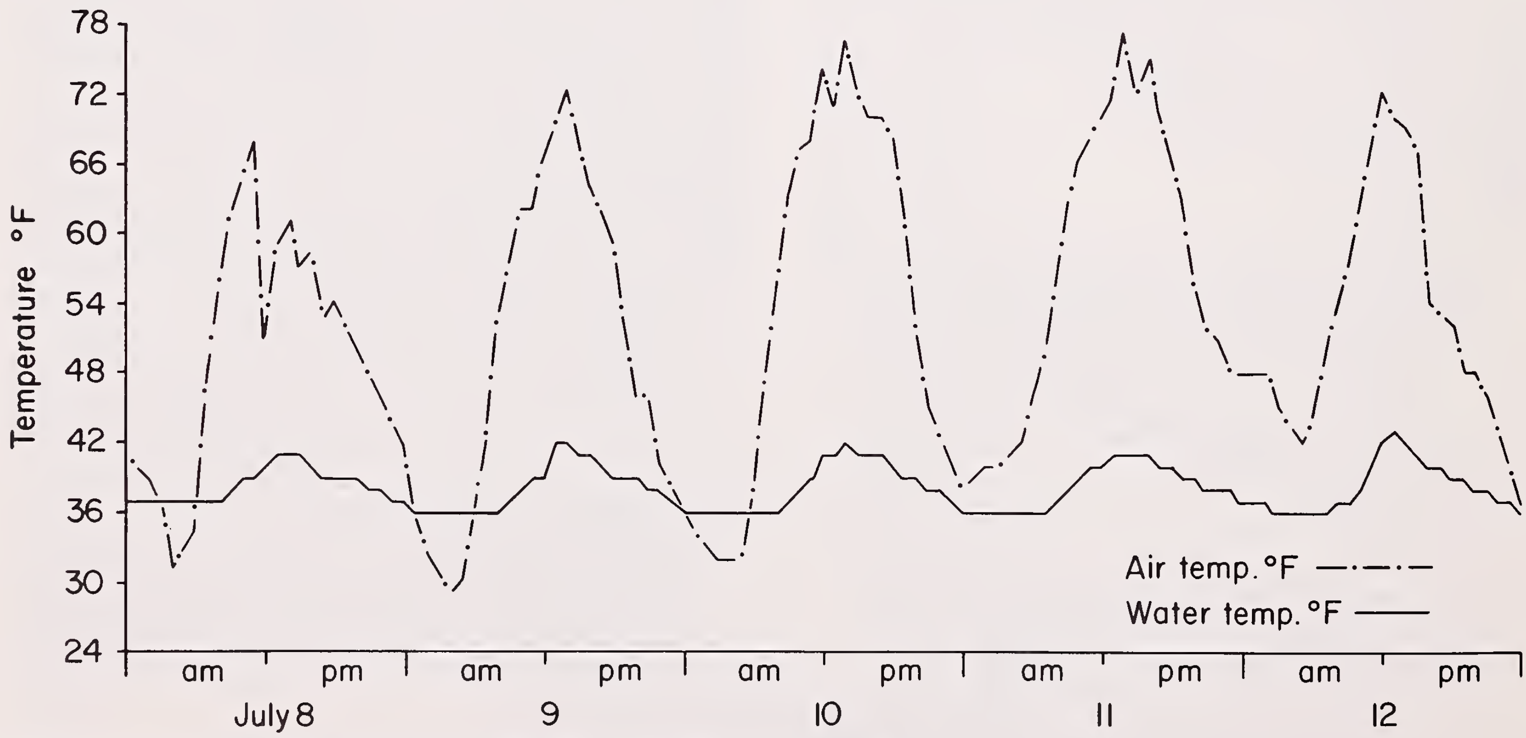

Figure 9. Daily courses of air and water temperatures at Fool Creek.

Combined with the roughness of the gravel bed, as well as other hydraulic components such as discharge, width, and slope, these energy dissipators led to relatively low velocities; most values ranged between 0.5 and 2.5 f.p.s. The average channel gradients of the reaches of the "rushing mountain streams" were 0.08 and 0.22.

Submergence of the steps would greatly reduce their effectiveness for energy reduction, and the present equilibrium of the streams, as will be discussed below, could be upset. Yet, based on 13 years of record, high flows that could lead to structural submergence occurred rarely.

When considering logs in the hydraulic geometry of small streams such as Deadhorse Creek and Fool Creek, an important contrast to gravel bars must be noted. Gravel bars are the result of stream action. They are "flexible structures" that change with flows (Kellerhals 1966). Log steps are inflexible structures if not washed out, reoriented by high flows, or rotted with time. Gravel accumulates and secures them in place. Only four locations could be found in both streams where logs had been washed out; it appeared that during flood stages the logs forced the flow around the structures and thus eroded their anchorage to one original channel bank. No evidence could be found that a gravel bar forced the flow out of its bed. Several years of record indicated only a few flows with possible higher than bankfull stages at the steps. Reorientation of logs that had fallen across the channel could not be verified, because many logs fell originally at different angles to the channel. Rotting led to loss of original height of log steps in some cases, and to breakage and loss of steps in others. Rotting appeared to be very slow.

Sediment load, normally a very important hydraulic parameter, was ignored in this investigation because the sediment yield was very small in both streams. This yield is derived mainly from a few extreme peak flows, but none occurred during the study periods.

Changes in width were minor due to rectangular channel cross sections. Cross sectional shape was expressed by the width-depth ratio and shape factor. The latter indicated loss of channel efficiency for conveyance of low flows, a fact which can be noticed by the casual observer. Within the range of flows experienced during the study, energy dissipation due to gravel and log steps as well as roughness of gravel beds and rock outcrops increased with decreasing discharge.

Reynolds and Froude numbers were in the expected range for tumbling, small mountain streams. However, in spite of heavy shading, the course of daily water temperatures was directly related to that of air temperatures. Water temperatures had a daily amplitude of up to 7°F during the middle of July.

The range of values of the exponents for the depth and velocity functions was relatively small. This indicates a certain degree of uniformity in the behavior of the hydraulic variables from station to station, which may be interpreted as an indication that Fool Creek had attained dynamic equilibrium. Discharges of Deadhorse Creek were too small during the study period to permit meaningful calculations. The dynamic equilibrium concept implies both stability and the ability to adjust; the term equilibrium can be interchanged with that of grade. But since many variables are involved in the channel-forming process that complicate any delineation of cause-and-effect relations, oversimplification must be avoided. However, Leaf (1966), in a study on sediment yield, also concluded that Fool Creek is a stream of grade. His conclusion was based on the uniform longitudinal profile concaved toward the sky, and the very small sediment load.

The study shed some light on the influence of streamside forests on the formation of steps in small mountain channels. It was shown that the streams required additional gravel bars to adjust to slope. On Deadhorse Creek, averaging 4.8 logs per 50 feet of channel, only 37 percent of the total steps were bars while on Fool Creek, averaging 2.5 logs per 50 feet of channel, 53 percent of the steps were bars. Thus less bed material moved at Deadhorse, although it had a much steeper channel slope than Fool Creek.

What is the forest management implication of the gravel bar-log step relationship? It appears that sanitation cutting (removal of dead and dying trees) should not be practiced along small mountain streams at dynamic equilibrium; the movement of bed material in such streams should be minimized. Such equilibrium is necessary, for instance, for maintenance of spawning beds for fish.

Literature Cited

Goodell, Bertram C.
1958. A preliminary report on the first year's effects of timber harvesting on water yield from a Colorado watershed. U.S. Dep. Agric., For. Serv., Rocky Mt. Forest and Range Exp. Stn., Stn. Pap. 36, 12 p. Fort Collins, Colo.

Hariri, Davoud.
1964. Relation between the bed pavement and the hydraulic characteristics of high-gradient channels in noncohesive sediments. Ph.D. diss., Utah State Univ., Logan, Utah, 109 p.

Judd. Harl E.
1963. A study of bed characteristics in relation to flow in rough, high-gradient, natural channels. Ph.D. diss., Utah State Univ., Logan, Utah, 182 p.

Kellerhals, Rolf.
1966. Stable channels with gravel-paved beds. ASCE Water Resour. Eng. Conf., Conf. Preprint 330, Denver, Colo., 38 p.

Leaf, Charles F.
1966. Sediment yields from high mountain watersheds, central Colorado. U.S. Forest Serv. Res. Pap. RM-23, 13 p. Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo.

Leopold, Luna B., and Thomas Maddock, Jr.
1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Surv. Prof. Pap. 252, 57 p.

Leopold, Luna B., Gordon M. Wolman, and John P. Miller.
1964. Fluvial processes in geomorphology. 522 p., San Francisco, London: W. H. Freeman and Co.

Love, L. D., and B. C. Goodell.
1960. Watershed research on the Fraser Experimental Forest. J. For. 58: 272-275.

Retzer, John L.
1962. Soil survey of Fraser alpine area, Colorado. U.S. Dep. Agric. and Colo. Agr. Exp. Stn., Ser. 1956, No. 20, 47 p.

Wolman, Gordon M.
1954. A method of sampling coarse riverbed material. Am. Geophys. Union Trans. 36: 951-956.

Wolman, Gordon M.
1955. The natural channel of Brandywine Creek, Pennsylvania. U.S. Geol. Surv. Prof. Pap. 271, 56 p.

Heede, Burchard H.
1972. Flow and channel characteristics of two high mountain streams. USDA For. Serv. Res. Pap. RM-96, 12 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Steps provided by logs fallen across the channel added to flow energy reduction. The streams required an additional number of gravel bars to adjust to slope. Average step length between logs and gravel bars are strongly related to channel gradient and median bed material size. More bars formed when fewer numbers of logs were available. Although these are "rushing mountain streams," most values for flow velocities ranged between 0.5 and 2.5 feet per second. Exponents of functions expressing rate of change of depth or velocity, respectively, with discharge, indicated that dynamic stream equilibrium was attained. Implications for forest management are that sanitation cuttings (removal of dead and dying trees) would not be permissible where dynamic stream equilibrium exists and bed material movement should be minimized.

Keywords: Mountain streams, hydraulic geometry, step formations, bed material movement, flood plain forest management.

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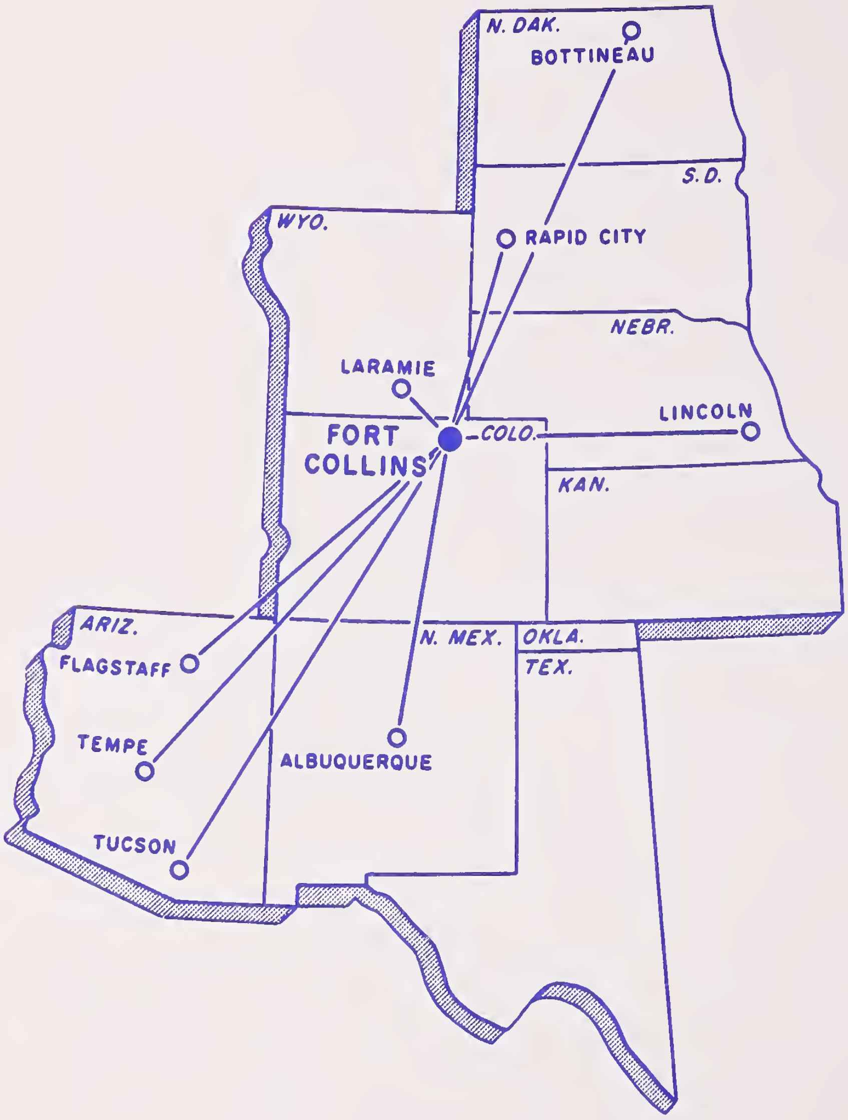
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